

# **Fire Hazard Assessment for Transportation Vehicles**

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One of the areas in which fire hazard assessment techniques have been applied within regulation is for transportation vehicles. In particular, commercial aviation and passenger rail have utilized fire hazard assessment as a means to achieve safety goals well before these techniques became common in buildings. This chapter will review the methods employed and the recent evolution of predictive tools specific to transportation. The reader should refer to the general chapter on Fire Hazard Analysis for an introduction to the basic principles. The American Society for Testing and Materials (ASTM) has developed a Standard Guide for Fire Hazard Assessment of Rail Transportation Vehicles, ASTM XXXX.<sup>i</sup> This document provides a detailed procedure for the conduct and documentation of a fire hazard assessment including specific design fire scenarios that should be considered.

## **Current Methods for Regulating Transportation Vehicle Fire Safety**

### *Aviation*

The Federal Aviation Administration (FAA) have pioneered the use of fire hazard assessment in the safety regulation of commercial aviation. As with most regulatory systems, the general objective is to protect passengers and crew from unreasonable risk of death or injury in accidents. The issue then becomes to reach some agreement on what is a reasonable or “acceptable” risk. Compared to other transportation modes, and especially private automobiles, the flying public is highly risk (and hazard) averse. Reflecting this concern, commercial aviation is highly regulated and (statistically) the safest mode of transportation.

A review of aviation accidents reveals that most occur on takeoff or landing. From a fire safety viewpoint, in-flight fires are extremely rare, especially in the U.S. When fire becomes a threat, it generally involves jet fuel spilled as a result of a crash. Where the crash itself involves high impact forces passenger and crew survivability is not possible. This observation led to the early recognition of a specific class of incident known as the “impact survivable, post crash fire” scenario. This is where most passengers and crew survive the crash and are subsequently capable of escaping the wreckage if given sufficient time.

Research conducted by FAA on commercial aircraft exposed to an external fuel fire indicated that the time available for passenger egress before flashover occurred in the cabin was approximately 90 seconds. Thus, the FAA established a regulation that commercial aircraft must be able to demonstrate that a full load of passengers can be evacuated within 90 seconds. Aircraft materials are tested to demonstrate that they are slow to ignite and burn such that the cabin environment can be kept safe for the 90 seconds needed for evacuation.

In the 1980's, the FAA promulgated a regulation that required aircraft seats to be protected against fire by a blocking layer between the outer covering and the cushioning. This regulation was supported by a cost-benefit analysis performed by NIST.<sup>ii</sup> This analysis incorporated the

impact of the mitigation strategy on the risk of death of passengers from in-flight, post-crash, and on-ground fires, and included normalization by exposure (in passenger miles) to allow extrapolation to potential future losses accounting for industry growth. The analysis further considered the historical record of aircraft fires as a means to establish current losses and scenarios. Because of the scarcity of incidents, worldwide incidents were included, but only those involving U.S. built, jet aircraft.

Another interesting approach from this study was the way in which evacuation times were considered. As discussed earlier, FAA regulations require that any aircraft be able to be evacuated within 90 seconds. But the study needed to determine the value of additional safe egress time provided by seat blocking that delayed flashover. Thus, the authors estimated the passenger evacuation rate from each exit, one-per-second from main doors (slower if the exit was partially obstructed) and one-per two-seconds for window exits or fuselage breaks. If a strategy resulted in 4 additional seconds of safe egress time and there were two main doors and two window exits available, the strategy was credited with saving 12 passengers.

### *Rail*

While all serious passenger rail accidents are investigated by NTSB, there has not been public pressure for strong safety regulation of rail transportation vehicles until recently. Following the 1996 Silver Spring accident where a Marc commuter train collided with an Amtrak passenger train resulting in 11 deaths, there was increased interest by the Federal Railroad Administration (FRA) to replace safety guidelines originally issued in 1984 and slightly revised in 1989, with regulations. These regulations, based on the guidelines but updated with information derived from NIST research were promulgated in 1999 <sup>iii</sup>.

The FRA tests and performance criteria cited in the 1999 regulations focus on providing a high level of fire performance for combustible materials found in vehicles. Like aircraft materials these are to be difficult to ignite and slow burning, producing limited smoke. Unlike aircraft that suffer severe operational penalties associated with weight, intercity and commuter rail vehicles and rail transit vehicles employ stronger construction including fire resistance requirements for floors, and for roofs when the vehicle is powered from an overhead catenary. Vehicles that make many stops recognize the energy penalties associated with weight and all involve much lighter construction than intercity passenger trains. The evolution of higher speed trains for intercity applications is bringing the energy issue forward here as well, so weight/cost trade-offs are becoming more universal. It should be noted the FRA tests and performance criteria are based on Federal Transit Administration recommended practices for rail transit vehicles published in 1984.

A review of rail accident scenarios reveals that collisions with vehicles at grade crossings or with other trains lead the list. Similar to aircraft liquid fuel spilled from the vehicle or train is the most common fire exposure. An example is an accident that occurred near Bourbonnais, Illinois in 1999 <sup>iv</sup> when a train struck a truck at a grade crossing. Leaking fuel from one of the locomotives ignited and engulfed a sleeping car where all the deaths occurred. Autopsies showed that four of the victims died due to fire, one died from carbon monoxide poisoning, and six died from physical injuries. Interior fires in moving vehicles are extremely rare with most such incidents involving small quantities of smoke from malfunctioning/overheating equipment.

There was a single-fatality, involving an Amtrak bi-level sleeping car (cigarette on a mattress) that occurred in 1982 in Gibson, California <sup>v</sup>.

### *Busses*

Busses are covered by only a few fire safety requirements . There are some controls on the flammability of interior linings and seats (FMVSS302) <sup>vi</sup>, fire resistive barrier around the engine compartment, and recent requirements for physical protection of the fuel tank against penetration. The great majority of bus fires are engine fires and the barrier provides adequate time to stop the bus and discharge the passengers. Some buses are equipped with fixed extinguishing systems for the engine compartment.

Following an 1988 accident in which a post-crash fire took the lives of 27 persons when a pickup truck struck a church bus in Kentucky, NIST conducted studies of the flammability of bus seats<sup>vii</sup>. Similar to the impact survivable post crash aircraft fire scenario discussed above this accident involved a leak from the bus fuel tank with fire penetrating through cracks in the floor and impaired exits. The crash destroyed the front door and the rear emergency exit was blocked by luggage in the aisle and rear seat.

An issue with school buses was the use of extra padding on seat backs and hand rails to protect occupants from injury in accidents (required by FMVSS222) because the use of seat belts was considered impractical. This additional padding increased the fuel load and fire development in a post-crash fire. Following the tests of current and potential seating materials in bench- and full- scale, HAZARD I (NIST's fire hazard assessment software) was used to examine the development of fire hazard to occupants from seating fires. The conclusions were that while two seating assemblies developed incapacitating conditions and one lethal conditions within three minutes, three other assemblies did not produce untenable conditions within the same time period <sup>viii</sup>. In 1993, the FTA published recommended practices for bus materials and engine compartments which cited the same tests and almost the same performance criteria as for rail transit.

### *Ships*

The regulation of commercial vessels is primarily conducted under international law. The International Maritime Organization (IMO) promulgates regulations and test methods for fire resistance and flame spread on interior materials. The US Coast Guard (USCG) enforces these and some other safety and sanitation requirements for foreign flag vessels that operate in US waters.

As a result of U.S. regulatory reform, the USCG initiated and chaired an NFPA technical committee to develop consensus standards as an alternative to the current fire regulations and NVICs <sup>ix</sup>. Various *NFPA 301, Code for Safety to Life From Fire on Merchant Vessels* requirements are described for vessels carrying more than 12 passengers <sup>x</sup>. Materials requirements are similar to the USCG regulations and the NVIC 9-97 with some exceptions. The passenger capacity, type of service (day or overnight), and whether or not the space is protected with automatic sprinklers determine flame spread limits. NFPA 301 means-of-egress provisions appear to be adapted for the marine environment from *NFPA 101 Life Safety Code* <sup>xi</sup> and depend on the number of passengers and whether or not overnight accommodations are provided.

NFPA 301 includes an appendix intended to allow the vessel designer and operator to comply with the Code while accommodating new or unique vessel uses or incorporating new or transfer technology. The appendix provides a standardized hazard analysis and risk assessment methodology to use in demonstrating equivalent safety. The methodology includes a description of several analysis techniques (e.g., preliminary hazard analysis, fault tree analysis, criticality analysis), data inputs (e.g., vessel physical description, design and operating assumptions and conditions), hazard correction measures, verification and documentation of equivalence

### **Application of Fire Hazard Assessment to Transportation**

The general process of fire hazard assessment as applied to buildings is also applicable to transportation. In this section the steps for conducting a FHA will be discussed in this context. The steps are:

1. Selecting a target outcome.
2. Determining the scenarios of concern.
3. Selecting design fires.
4. Selecting appropriate calculation methods.
5. Performing an evacuation calculation.
6. Analyzing the impact of exposure.
7. Accounting for uncertainty.

### **Selecting a Target Outcome**

The objective of safety regulations for transportation is to minimize loss of life and injuries in accidents. Preservation of property, in particular the limitation of damage to the vehicles, is not considered. Thus, regulations focus on vehicle design, material selection, and emergency procedures that would be expected to mitigate human losses in accident scenarios drawn from operating experience. However, since transportation accidents that involve fire are exceedingly rare, hazard scenarios that have been considered include possibilities that may not have actually occurred.

### **Determining the Scenario(s) of Concern**

Scenarios to be evaluated can be drawn from the detailed NTSB accident investigation reports and the operational experience of the industry, but should be supplemented by reasonable scenarios that could result in significant threat to passengers or crew. For example, NIST research conducted for the FRA identified trash bags found on overnight trains as a potentially significant fire exposure (250 kW) to seats and interior materials, even though there are no records of fires involving these trash bags on trains.

Vandalism is a source of fires in subways and commuter rail systems. Scenarios may involve newspapers and small amounts of flammable liquids used to ignite seats, that may be slashed to expose interior padding. Some operators require fire testing of seats that have been slashed in an “x” pattern low on the back and through the upholstery.

Tunnels represent a significant complication in a rail environment. Accidents that may occur in a tunnel pose an additional threat to passengers and crew because the fire effluent is contained around the train where it can continue to expose people who have exited the vehicles. Tunnels,

bridges, or other elevated track sections also restrict the ability of people to move to a safe location away from the train. These issues need to be addressed where trains operate in long tunnels or have extended elevated sections.

### **Selecting the Design Fire(s)**

In both the aviation and rail environments, the materials employed for seating and finish are high fire performance materials and systems. Thus, burning rate data on actual materials should be used wherever possible because data on typical materials will not be applicable. Care should be exercised because burning rates may be reported only at higher incident fluxes because the materials do not burn at typical flux levels. The “T-squared” fire curve still can be used where large scale burning rate data on actual transportation materials is available and can be shown to correlate to the T-squared growth rate employed.

### **Selecting Appropriate Methods for Prediction**

Particular care should be exercised in the selection of appropriate prediction methods for transportation applications. Planes and trains are spaces with large aspect ratios so some aspects of zone models may not be appropriate. Aircraft operate under conditions of pressurization to about 8,000 feet, so oxygen levels and partial pressures are lower than normal. Their ventilation systems are unique and can have a significant influence on fire development and smoke movement. Train ventilation systems are more like those found in buildings and should not represent special circumstances.

### **Performing an Evacuation Calculation**

In all transportation modes except aircraft it is necessary to perform an evacuation calculation to estimate the time needed for passengers and crew to move to a safe location. In aviation, passengers and crew must await landing the plane before any egress actions can begin. Once the aircraft comes to a stop, as defined in FAA regulations it can be assumed that everyone can be evacuated within 90 seconds through half of the available exits. This 90 second emergency evacuation performance is demonstrated for every commercial aircraft and configuration with a full load of passengers having a distribution of gender and age approximating that of the flying public in order for an aircraft to be certified.

The limitations are that these evacuation certification tests are performed under the nearly ideal conditions with the aircraft upright and level and without smoke. Most of the test subjects are employees of the aircraft manufacturer (and as such are usually experienced in emergency evacuation of the aircraft), and none attempt to take carry-on items as is often reported in actual aircraft evacuations.

In a rail environment, there is no such requirement for evacuation performance and little research or testing from which to obtain details of passenger egress behavior. In trains, passengers are always free to move about, so passengers might be expected to begin egress behavior from one car to another while the train is still moving, although they would have to sit or hold on during any emergency braking. Current emergency procedures for rail vehicles emphasize movement to safe areas in adjacent cars, even when the train is stopped. However, if passengers get off the train, they may be struck by other trains passing on an adjacent track; use of escape windows is only a last resort because many are located too high off the ground. If an emergency occurs

while a train is in a tunnel, the train would continue moving until it is clear of the tunnel, if possible. Compared to aircraft usually consisting of a single main cabin and a specified number of flight crew for the number of passengers, a train has many fewer crew per passenger and passengers may be seated in several separate cars. Train crew would use the public address system to issue emergency instructions but would likely have less direct contact with passengers.

A number of special evacuation characteristics for train cars should be considered in any evacuation calculation. Horizontal travel speeds in a moving train car would be expected to be significantly slower than walking speeds in buildings. Some commuter and intercity trains use bi-level car designs with one or two stairways per car. These stairways are narrower and steeper than building stairs so travel speeds should be slower. Most such cars have lateral connections on both levels but there are some notable exceptions – Amtrak double deck sleepers have no lateral connections to adjacent cars on the lower deck. Such details should be accounted for in evacuation calculations.

### **Analyzing the Impact of Exposure**

In any fire hazard assessment the impact of exposure of people to fire effluent is related to concentration and time. An aircraft experiencing an in-flight fire scenario would be expected to involve a significant exposure time since the typical time to affect an emergency diversion is estimated by the FAA to average about 30 minutes. Thus, even low concentrations of fire gases can lead to impaired egress performance. For the impact survivable, post-crash fire scenario the exposure time is (by FAA definition) not greater than 90 seconds, so only thermal threats would be of significance.

In a rail environment, most scenarios of interest would find safe areas in adjacent cars with short movement times to areas of relative safety. Thus, most rail scenarios would involve short exposure times where primary threats would be from thermal insults. One exception is in sleeping cars not equipped with fire detection systems and where the incident occurs in a long tunnel.

### **Accounting for Uncertainty**

One of the more difficult aspects of conducting a fire hazard analysis is the estimation of uncertainty. Where there are data from full-scale tests these can be used to estimate the uncertainty of a calculation method applied to the same conditions (see following section for an example). In the absence of data a sensitivity analysis might be performed to quantify the effect of uncertainty on the outcome.

### **Alternative Uses for Fire Hazard Assessment**

The preceding has focused on the use of fire hazard assessment in the evaluation of the performance of a specific transportation system design against the objective of passenger and crew safety. Another application of fire hazard assessment techniques might be to determine the minimum performance level of a major system component necessary to meet the target outcome. An example of such appears in the Phase III report of NIST's research for FRA<sup>xii</sup> of passenger rail fire safety, where the hazard assessment supports the regulation of the fire performance of materials in their context of use in the vehicles.

For the car designer or regulator, the objective is to determine the limiting performance level so that the designer has the freedom to use any material in any way that will not violate this bounding condition. Thus, a *fire performance curve* was calculated with NIST's CFAST fire model and applying tenability criteria to obtain time to impaired evacuation and incapacitation as a function of fire growth rate for a typical intercity rail (single deck) coach car. The fire performance curve shows that any fire that does not exceed the medium (T-squared) growth rate will not pose a threat to passengers or crew.

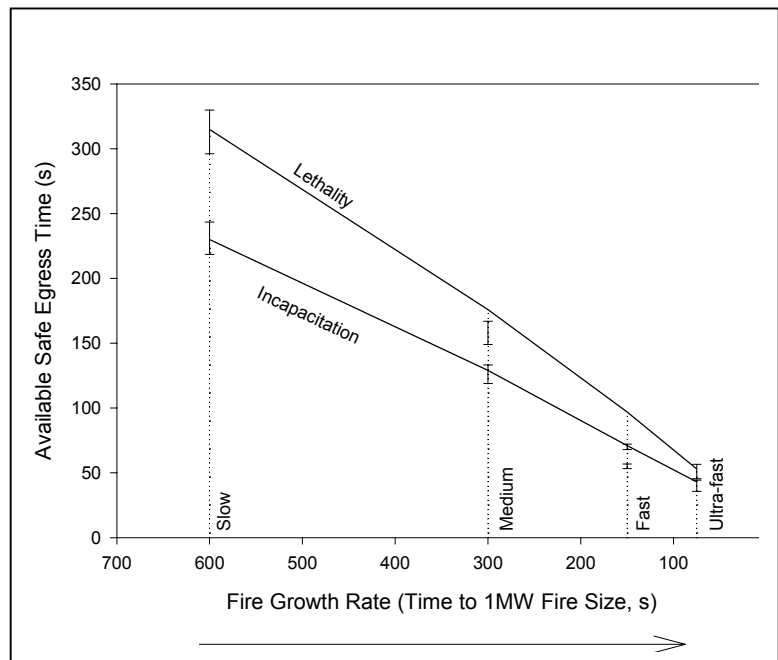


Figure 1 shows the fire performance curve determined from experimental measurements in the gas burner tests along with fire model predicted curves calculated for the test vehicle. For a medium growth rate t-squared fire, the time to incapacitation determined from the replicate gas burner tests was  $(126 \pm 7)$  s. For other growth rate fires, the time to incapacitation ranged from  $(40 \pm 4)$  s for the ultra-fast growth rate fire to  $(230 \pm 12)$  s for the slow growth rate fire. On average, the uncertainty of the experimentally determined times to these untenable conditions was less than 7 percent (based on one standard deviation). Once the bounding condition, in this case a medium T-squared fire growth rate, is known the vehicle designer or regulator can use any of several means to assure the limit is not exceeded – including material selection, limiting quantities of combustibles, active mitigation strategies such as suppression or smoke venting, etc.

### Application of Fire Hazard Assessment to Passenger Rail

Recent revisions to 49CFR, Part 238, Section 238-103 (d) requires that railroad operators conduct a fire safety analysis on all categories of existing passenger railroad equipment and service. The industry, through the American Public Transit Association is developing guidelines for conducting this analysis. The following is intended to demonstrate that process and to produce a recommended practice to guide the industry in meeting the intent of the regulation.

The first issue that needs to be addressed is to understand the intent of the regulation. This is, to conduct a systematic analysis of railroad equipment and service that will identify potential fire hazards to passengers and crew and to take steps to mitigate these potential hazards. Where multiple, potential hazards are identified mitigation should be prioritized in order of decreasing risk.

This intent embraces several important concepts. The first is the fire scenario. A *fire scenario* is a description of the sequence of events that must occur to result in an uncontrolled fire. A fire scenario description generally includes an ignition source and an initial item ignited, but may

include other, special conditions that are required to result in the consequence to be avoided. For example, some fire scenarios may only represent a threat to passengers and crew if they occur in a tunnel that increases the smoke exposure or if the passengers have limited ability to evacuate without assistance.

The second is fire hazard assessment. A *fire hazard assessment* is a systematic examination of all potential fire hazards that might occur, resulting in the consequence to be avoided, in this case an injury or fatality to passengers or crew. Note that a fire hazard assessment is not limited to fire hazards that have at some time occurred, but should also consider fire hazard scenarios that are possible, even if they would require several things to go wrong simultaneously.

The third is fire risk assessment. A *fire risk assessment* begins with a fire hazard assessment and weights the consequences by the likelihood of the fire scenario. By discounting the consequence by likelihood the scenario with high consequences and low likelihood and the scenario with low consequences but occurs frequently have represent equal risk. Thus, fire risk analysis is a way of normalizing different hazards so that they can be compared or summed to produce a total threat index.

## **Define Scenarios**

The first step in the process is to define the scenarios which could lead to potential injury to passengers and crew. These will include both those fire scenarios that have occurred and those that are possible but have not yet occurred. Traditionally the former are identified from accident statistics and reports, although, in most cases, the reporting systems have significant shortcomings and the data bases are incomplete. Federal regulations (49CFR, Part 225) require that incidents that result in a fatality or injury, or result in damage to property exceeding a threshold (\$6700 for 1998) be reported. A recent search of this data base identified 156 fire incidents of interest for 1985 to 1998.

Additionally, there are other fire data bases that can be examined, such as the National Fire Incident Reporting System (NFIRS). A recent search of NFIRS for passenger rail fire incidents for the ten year period from 1988 through 1997 identified 71 fires resulting in two civilian deaths and four injuries. Note that such searches should not be limited to those that resulted in fatality or injury because the intent is to identify scenarios that may result in fatality or injury. No scenario should be excluded unless it is determined that it cannot result in harm under any condition.

Defining scenarios that have not occurred requires judgment and experience. They may involve new combinations of ignition sources and fuels, or they may involve new items not previously found in the rail environment. An example would be electronic equipment introduced to entertain passengers or to facilitate work during transit. At this stage, it is best to include everything possible and to cull the list later with justification. Also, since the rail operator is performing the analysis, it should be possible to identify incidents that did not exceed the reporting threshold but are documented internally or in the experience of employees.



## **Inventory of Equipment - Identification of Hazards**

The fire safety analysis will need to be conducted around an inventory of equipment and materials that make up the vehicle. Anything that uses energy or materials that are easily ignited by small sources such as matches or smoking materials should be identified as potential ignition sources. Any combustible material can be a first-item-ignited, or a fuel item. The inventory should also identify items in both categories that may be brought aboard by passengers such as luggage, packages, and even coats and pillows.

Each of these items needs to be characterized in terms useful to the fire safety analysis. Ignition sources are characterized by maximum potential energy; fuel items by heat release rate (HRR) and yields of smoke and gases, as well as some measure of ignitability.

At the same time the equipment or design features present that may mitigate hazards or impact on the evolution of hazard should be identified. These vehicle characteristics include number, type, and location of doors and escape windows/hatches; number of levels and stairways; detection, extinguishing, communication, emergency lighting and signage, or smoke management systems.

## **Analysis of Operating Environment**

The operating environment of vehicles has a significant influence on the fire hazards that may be encountered. Operating speeds, grade crossings and their protection; bridges and tunnels; shared right-of-way with freight operations; and even terrain can affect the analysis and should be identified.

## **Description of Fire Scenarios**

Using this inventory the combination of ignition sources and fuels that can result in a significant fire becomes the basis of a fire scenario description. For example, if a piece of electrical equipment is protected by a fuse so the maximum fault energy is limited, and it is enclosed or separated by a distance from any combustible material so that this maximum fault energy cannot ignite the fuel, then this scenario can be eliminated at this step. Of course, the possibility of the wrong size fuse resulting in a higher fault energy or combustible materials that are “not supposed to be there” need to be considered as separate scenarios.

## **Fire Hazard Assessment**

For each of the identified fire scenarios, the consequences of the hazards in terms of potential injuries or fatalities to passengers or crew is evaluated. This evaluation is done in any of several ways. First, the judgement of experienced people can be used to determine likely outcomes of some scenarios – especially those for which historical experience exists.

Second, there are various tools to assist in making a determination. These include fault trees such as NFPA550 or simple calculational procedures such as FPEtool. These methods depend on judgement supported by individual calculations to provide quantitative results.

Third, there are more detailed modeling tools such as HAZARD I, that are increasingly being applied to special areas such as rail. In addition to providing predictions of the outcome of specific scenarios, these tools can be used to estimate general, bounding conditions in the form of fire performance curves as demonstrated in the NIST Phase III report (in press).

The important criterion in the fire hazard assessment is not only to identify conditions or design features that relate to identified hazards, but to determine that the conditions or features actually mitigate the hazard. For example, a fire-rated floor may provide protection against ignition from an overheated wheel, but if combustible lubricants are allowed to build up on the wheel assembly the overheated wheel may ignite the grease that then may present too great a heat source for the floor to provide adequate protection.

### **Risk Ranking**

Once each of the fire hazard scenarios have been evaluated, those which may potentially result in injury or fatality to passengers or crew and are not already addressed by design or operating procedures will have been identified. Mitigation strategies for each should be suggested and evaluated for effectiveness by re-running the hazard calculation with the strategy in place. Only where it is not practical to eliminate all identified hazards is it necessary to perform a risk ranking to prioritize those situations to be addressed first.

Here, the likelihood of the remaining scenarios is estimated from historical data or experience. Then this likelihood is used to discount the consequences of each remaining scenario so that the risk of each can be compared. For example, if one scenario is expected to result in 10 passenger injuries and another in 50 passenger injuries, but the first is 10 times more likely, the first is the higher risk and should be addressed first.

Ideally, one would like to be able to define a level of “acceptable risk” below which it is not necessary to take remedial action. Unfortunately this is a very difficult task since risk perception and risk acceptance is quite variable. Normally the “reasonable person” does not expect to be protected from reasonably unexpected hazards or hazards clearly beyond control. An example of the former is to design a train to withstand being struck by a falling airplane. An example of the latter is designing against a terrorist attack.

Beyond these “reasonableness” tests, experience has shown that the public is more hazard averse than risk averse. Transportation accidents resulting in large numbers of fatalities or injuries are considered unacceptable, regardless of a demonstrable low likelihood. Thus, the concept of “acceptable risk” may not be applicable.

### **Conclusions**

Modern fire hazard assessment techniques that are becoming common in the building regulatory arena can be adapted and applied to transportation. While transportation has an excellent fire safety record, these new techniques are desirable because they provide increased design flexibility particularly with respect to the introduction of innovative materials.

Recent research into fire hazard assessment for passenger rail has resulted in the promulgation of regulations and the development of procedures that can be used by the industry for compliance. These techniques also have application to other transportation sectors such as transit and may be adapted for use there in the future.

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